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13. ABSTRACT (Maximum 200 words)

"Sagnac Spectroscopy" is performed by monitoring the change in beat note between counterpropagating beams in a ring laser, while linearly scanning the difference in cavity frequencies for opposite directions. With a sample of Samarium inserted in the laser, resonances associated with the hyperfine splitting are observed, with a resolution better than 10kHz, even though the laser bandwidth exceeds 1THz. The measurements performed leads to a complete determination of the 3x3 density matrix of a Λ or V level system.

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1 Introduction

The fact that the two counterpropagating pulses in a mode-locked dye ring laser can be completely decoupled in freqeuncy, makes such a laser a sensitive probe of phase differences between the counterpropagating pulses. The difference in center frequency between the two counterpropagating pulses can be resolved down to the noise limit of 100 Hz. This limit corresponds to a phase difference between the counter propagating pulses of 10^{-6}, or an effective cavity length difference of 10^{-12} m. This high sensitivity to non-reciprocal phase differences can be used for gyroscopic measurements [1, 2], intracavity electo-optic sampling, and intracavity spectroscopy [3].

2 Intracavity spectroscopy of samarium

The sensitivity of the mode-locked ring laser is presently exploited to make phase-sensitive spectroscopic measurements inside the ring laser cavity. Such measurements use the detected beat frequency between the counterpropagating pulses to infer magnetic field splittings and study coherent interactions in a three level system. Samarium vapor has been chosen for this study because it has two well suited transitions between J=1 and J=0 energy levels at 571 nm and 654 nm [4, 5]. The coherent interaction of radiation with a three level system has received much attention recently due to the possibility of observing giant indices of refraction and gain without inversion [6, 7].

2.1 Measurements with vapor cell

A passively mode-locked ring dye laser is modified as shown in Fig. 1 to create a linear "tail" where a heated cell (5 cm long) containing atomic samarium is inserted. The presence of the wave plates and the calcite polarizing beam splitter ensure that the counterpropagating pulses from the ring are orthogonally polarized (circularly right and left) when they travel through the cell. The adjustable Faraday cell in the tail is used to create a non-reciprocal path length difference between the counterpropagating pulses. This simply results in a constant bias beat frequency of anywhere from 0-2 MHz. With the entire interaction region surrounded by three orthogonal sets of Helmholtz coils, stray magnetic fields are eliminated and a uniform field can be applied along the direction of laser propagation. The laser is tuned to resonance with the $J = 1 \rightarrow J' = 0$ transition of samarium at 654 nm, and the longitudinal magnetic field is scanned to Zeeman-split the degenerate ground state, creating a three level Λ structure. The range of the magnetic field scan is chosen appropriately so that the lower level splitting of the Λ structure is scanned about the level splitting which corresponds to the bias beat frequency. It is at the point where the bias frequency equals the level splitting that a resonance is expected. The left and

right circularly polarized pulses each interact with only one branch of the Λ structure. These interactions transfer population between the $m_j = 1$ and $m_j = -1$ ground states via the excited state and create a coherence between the two ground states. The result of this coherence is an enhancement of the normal Faraday rotation and is observed in the measurement of the beat frequency between the counterpropagating pulses.

An example of the experimental results is shown in Fig. 2. The upper part of the figure shows the actual sampled data consisting of the beat frequency and the triangle voltage proportional to the magnetic field in the cell. The measured beat frequency is the difference between the true beat frequency and a reference oscillator at 1.0950 MHz The lower part of the figure shows the Fourier transform of the beat frequency as a function of the magnetic field. This is obtained from the data in the upper part of the figure. As can be seen, the beat frequency has the characteristic shape of a dispersion curve with a half-width of approximately 3 G which corresponds to a level splitting of 12 MHz for the samarium atoms. We note that this width is much less than both the bandwidth of the pulse (2 GHz) and the Doppler broadened linewidth of the transition (800 MHz). We believe such results are characteristic of nonlinear Faraday rotation and are in qualitative agreement with those made by Drake [4]. We further note that the dispersion curve is centered about the level splitting which is equal to the bias beat frequency as applied with the Faraday cell.

2.2 Measurements with an atomic beam

An alternative configuration involves an intracavity atomic beam, which has the advantage of minimal Doppler broadening. The setup for these measurements is shown in Fig. 3. The samarium atoms in a well-collimated beam traveling perpendicular to the k-vector of the laser interact with the resonantly tuned laser. Once again, the entire interaction region is surrounded by three sets of Helmholtz coils to eliminate all stray magnetic fields. If a magnetic field is applied along the direction of light propagation, the degenerate upper (or lower) level of the transition is split. Because of the presence of the quarter wave plates in the cavity, each of the counterpropagating pulses interacts only with the σ^+ or σ^- branches of the three level "V" or "Λ" transition. As the longitudinal magnetic field is scanned around zero, the difference in phase experienced by the counterpropagating pulses appears as a modulation of the beat frequency. An alternative approach involves fixing the magnetic field so that a level splitting of a few megahertz is obtained. The frequency of the counterpropagating modes can be scanned by varying the voltage applied to the Pockels cell [3], or by using a Faraday cell as described in the previous section. When the *difference* in frequency between the counterpropagating longitudinal modes is equal to the level splitting,a resonance is expected in the beat frequency. The position of the resonance directly yields the magnetic field splitting which can be measured down to the

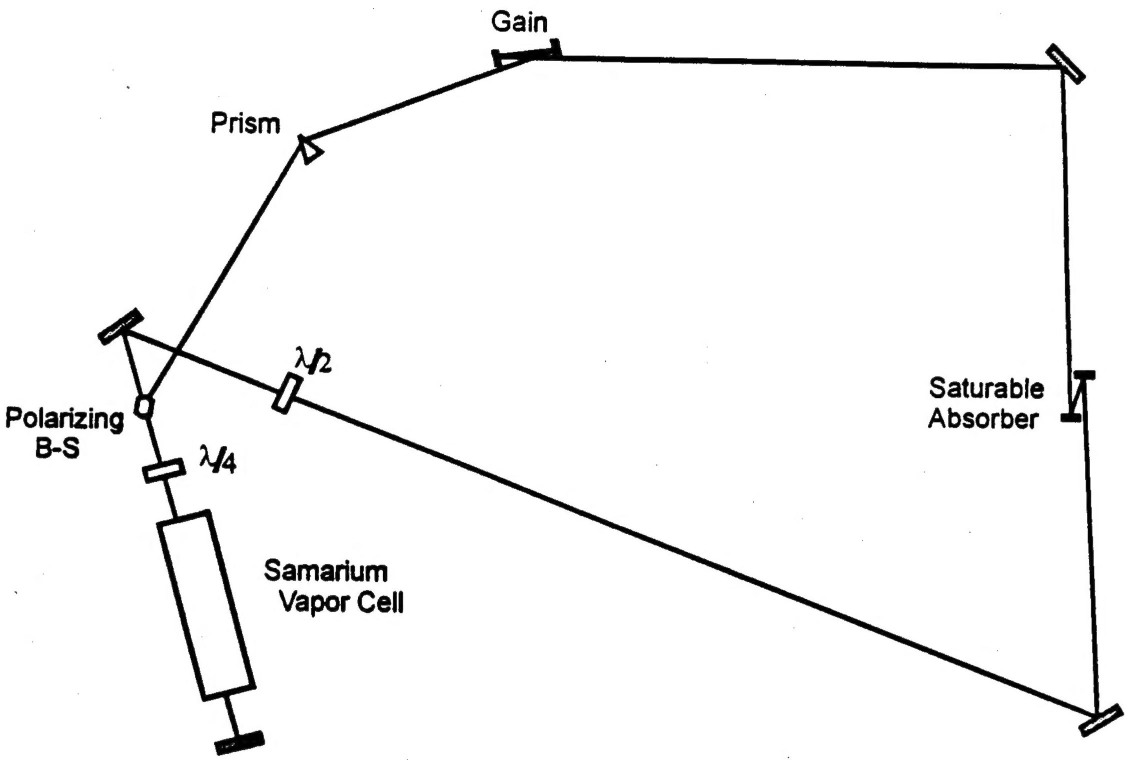
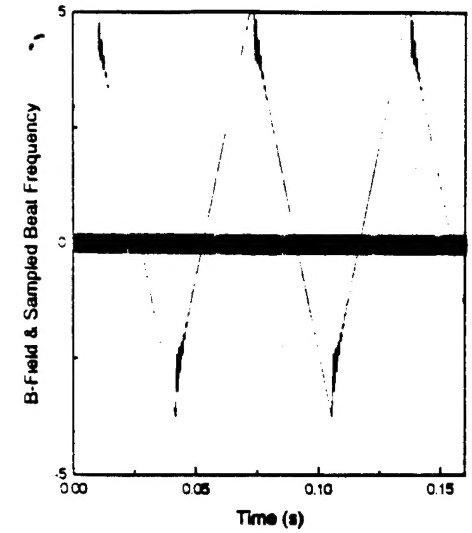


Figure 1: Modified passively mode-locked ring dye laser. The two counterpropagating pulses are made to travel through a linear "tail" where they interact with samarium vapor. Phase differences introduced between the counterpropagating pulses are manifest in a beat frequency between the pulses.



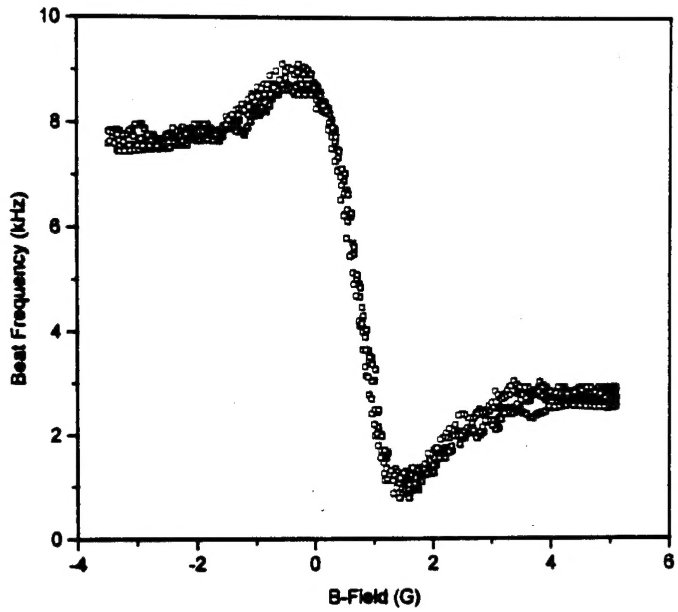


Figure 2: Sampled beat frequency (difference between true beat frequency and 1.0950 MHz reference oscillator) and voltage applied to Helmholtz coils (upper). After callibration of the magnetic field and a Fourier transform of this sampled data, we obtain the beat frequency as a function of the magnetic field applied to the samarium vapor (lower). The data were accumulated with 5 scans of the magnetic field.

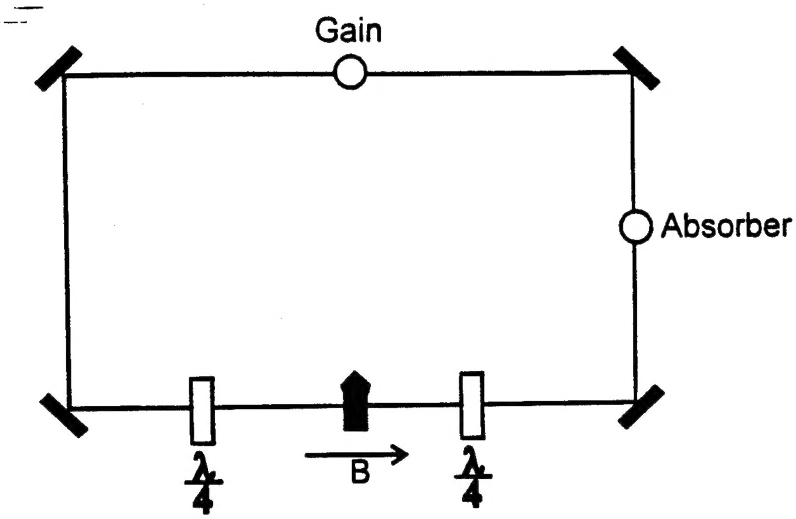


Figure 3: Experimental setup for phase-sensitive spectroscopic measurements on an atomic beam inside the cavity of a mode-locked dye laser. The levels of the samarium atoms are split by a longitudinal magnetic field. The linearly polarized counterclockwise beam is made right circular by a $\lambda/4$ plate, and thus interacts only with the σ^+ transition. The clockwise beam is made to interact solely with the σ^- transition after passing through the second $\lambda/4$ plate.

same 100Hz resolution obtained in the gyroscopic rotation measurements. For samarium, this corresponds to a sensitivity to magnetic field splittings of close to 10^{-5} G. In the course of making the measurement described above, it was discovered that cavity length instabilities made it difficult to keep the laser tuned to resonance. This is only true with the atomic beam because of the small of Doppler broadening, which is estimated to be on the order of 30 MHz. This is less than the longitudinal mode spacing of the laser, so that it becomes crucial to have the laser cavity frequency stabilized.

3 Stabilized mode-locked laser

As just mentioned in the prevous section, due to mechanical vibrations and thermal gradients. the longitudinal modes of the cavity move about. Clearly, this is not desirable when doing high resolution spectroscopy. The Pound-Drever-Hall stabilization scheme [8]

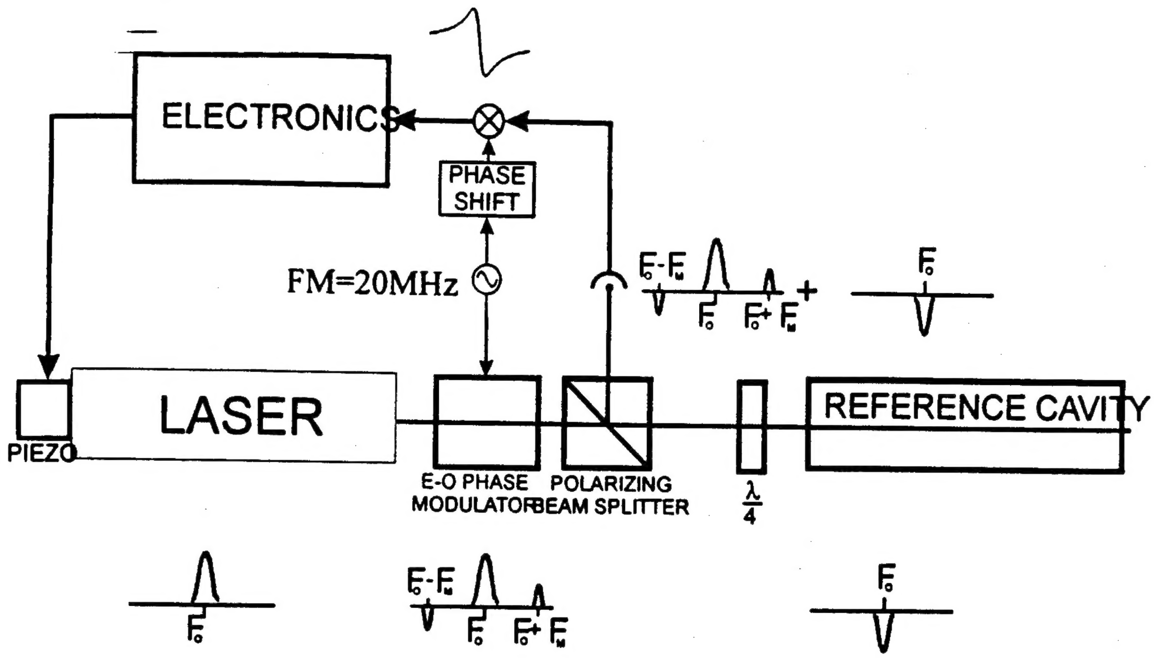


Figure 4: Schematic of Pound-Hall-Drever stabilization scheme.

is implemented to stabilize the longitudinal modes to a reference cavity with a 3MHz bandwidth as shown in Fig. 4. The reference cavity is an Ultra-Low-Expansion block of quartz with mirrors optically contacted on the ends to produce a confocal cavity. This stabilization technique is now being applied to a mode-locked ring cavity where many modes are present. The cavity lengths must be integer multiples of one another for sufficient energy to build up in the reference cavity for stabilization to occur.

Initial results from the stabilized mode-locked laser are shown in Fig. 5. The upper graph shows the digitally sampled beat frequency with the unstabilized laser. As can be seen, the beat frequency is not well defined because it is at the same level as the noise. However, with the cavity stabilized the beat frequency can be distinguished from the noise, as shown in the lower plot. A Fourier transform of this data yields a beat frequency of 125 Hz. With improvements in the laser and the stabilization electronics, it is anticipated that beat frequencies as small as 0.05 Hz could be resolved. This would place the sensitivity of the system close to the quantum limit [9].

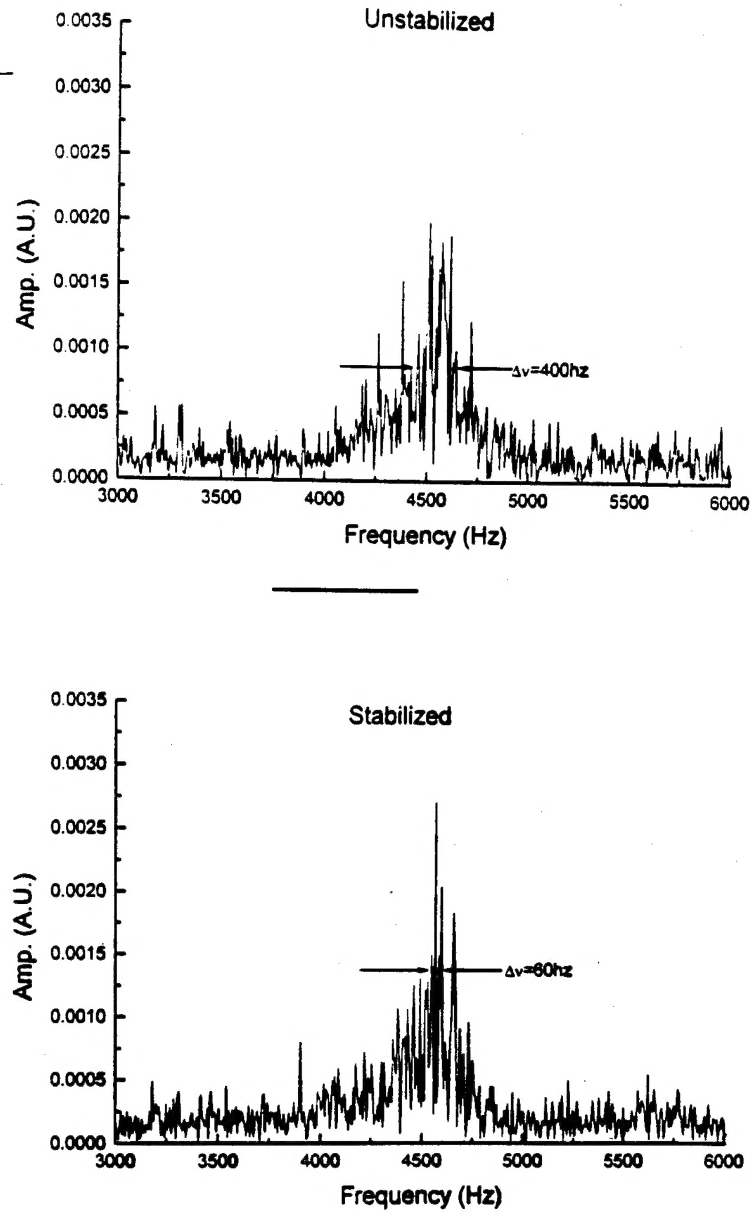


Figure 5: Beat frequency for the unstabilize (top) and stabilized (bottom) mode-locked laser.

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